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Interface state energy distribution from non-ideal (I–V) characteristics of Ni/n-Si Schottky barrier diode*

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Abstract : Experimental technique recently developed by Horvath and Kovacs has been used for characterizing interface state energy distribution in Ni/n-Si Schottky barrier diode from the non-ideal (I–V) characteristics The interface state density in the structure studied, has been found of the order of 10^{12} cm^{-2} eV^{-1}

Keywords : Schottky barrier diode, interface state energy distribution, (I–V) characteristics

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1. Introduction

The study of Schottky barrier formation at metal-semiconductor interfaces has been of long-standing scientific and technological interest because of their wide applications in modern semiconductor device technology. Some of the devices based on Schottky barrier junctions are photodetectors, solar cells, laser diodes, MOSFET, nuclear particle detectors, IR detectors *etc*. The applications also include the use of Schottky barrier junctions for characterising semiconductors. The major task for understanding the properties of a Schottky barrier junction is the characterization and description of interface states.

Recently, Horvath and Kovacs [1] have developed a technique for the evaluation of the energy distribution of interface states from non-ideal current-voltage (I–V) characteristics of the Schottky barrier diode. This technique is based on the model of an interfacial layer at the metal-semiconductor interface, and the presence of interface states at the semiconductor surface. In this case, the non-ideal (I–V) characteristics are due to the

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bias dependence of the barrier height and to the series resistance of the junction. The bias dependence of barrier height is caused by the image force lowering, the interfacial layer and the interface states. Taking these into account, Horvath [3] developed this evaluation technique for two different models concerning the quasi-Fermi level positions in Schottky diodes. In model A, it is assumed that for the forward direction, all interface states are in equilibrium with the semiconductor while for the reverse direction with the metal. In model B, it is assumed that for the forward direction all interface states are in equilibrium with the semiconductor, while in the reverse direction their common density (the change of the interface charge) is negligible.

In the present paper, this technique has been used for characterizing interface state energy distribution in Ni/n-Si Schottky barrier diode from the non-ideal (I–V) characteristics.

2. Theoretical approach

Generally, most practical metal-semiconductor interfaces are not ideal, but instead are, metal-thin interfacial layer-semi conductor (MIS) structures due to inadvertent presence of a thin interfacial layer produced during processing. Such inadvertent interfacial layer can arise due to oxide layers, chemical reactions, cross-diffusion *etc*.

Due to the presence of the interfacial layer, the bias applied is divided among the series resistance (V_r), the interfacial layer (V_i) and the semiconductor depletion region (V_s) :

$$V = V_r + V_d = V_r + V_i + V_s,$$

where V_d is the voltage drop across the junction ($V_d = V_i + V_s$). The (I–V) characteristics of the most Schottky barrier diode is characterized by the thermoionic emission theory. Thus, assuming interfacial layer-thermoionic (IT) current transport mechanism in these diodes, the quantities V_i and V_s for both forward and reverse biases can be obtained from the equations [2] :

Forward bias case,

$$J_f = A^* T^2 \exp\left[-q(\phi_{bo} - \Delta\phi_{bf} + V_{if})/kT\right] \left[\exp(qV_{df}/kT) - 1\right] \tag{1}$$

Reverse bias case ($V_d < 3kT/q$),

$$J_r = A^* T^2 \exp\left[-q(\phi_{bo} - \Delta\phi_{br} - V_{ir})/kT\right] \tag{2}$$

where J is the current density, A^* the effective Richardson constant including the transmission probability across the interfacial layer, T the absolute temperature, q the magnitude of electronic charge, ϕ_{bo} the zero-bias barrier height, $\Delta\phi_b$ the image force barrier lowering and k the Boltzmann constant. The suffixes f and r represent the forward and reverse bias cases. From the plots of V_i *vs* V_d, the derivative (dV_i / dV_d) has been found for both forward and reverse biases. This derivative is the same as the bias dependence of barrier height due to the interfacial layer and interface states, characterized by $\beta(=d\phi_b / dV_d)$.

Knowing the derivative (dV_i/dV_d) as a function of V_d, the slope of the forward characteristics (characterized by n) and the slope of the reverse characteristics (characterized by s) are obtained from the equations [3] :

$$n = 1/(1 - \beta) \tag{3}$$

and

$$s = q\beta/kT. \tag{4}$$

The occupancy of an interface state lying within the semiconductor bandgap depends on the charge exchange between the interface state and the three reservoirs surrounding it, namely the conduction and valance bands of the semiconductor and the conduction band of the metal. The charge exchange between the semiconductor conduction or valence bands and the interface states follows the Schokley-Read-Hall (SRH) theory while the charge exchange between the interface states and the metal conduction band occurs through direct tunnelling. It has been shown that the occupation function of interface states remains unchanged for almost all bias condition except when the diode is forward biased [4]. Hence, we conclude that all interface states are in equilibrium with the semiconductor for the forward direction while the change of the interface charge is negligible for the reverse direction [Model B]. The interface state density (D_s) and the relative interfacial layer thickness [ratio of the interfacial layer thickness (δ) to its relative dielectric constant (ε_i)] for Model B are given by the equations [3] :

$$D_s = (\varepsilon_0/q)\left[(\varepsilon_s/W_r)(q/skT - 1)(n - 1) - (\varepsilon_s/W_f)\right] \tag{5}$$

and

$$\delta/\varepsilon_i = \left[(\varepsilon_s/W_r)(q/skT - 1)\right]^{-1}, \tag{6}$$

where ε_0 is the dielectric constant of vacuum, ε_s the relative dielectric constant of the semiconductor, W_f and W_r the widths of depletion regions in forward and reverse bias cases.

3. Experimental details

Ni/n-Si (111) Schottky diodes were fabricated by the vacuum vapour deposition of Ni at ~ 10^{-5} torr pressure on an n-type <111> oriented silicon wafer with a resistivity around 6–8 Ω cm. Details of fabrication technique have been described elsewhere [4,5]. Dark (I–V) measurements were taken by means of HP 414OB pico-ammeter. All measurements were conducted at room temperature (300 K).

4. Results and discussion

The (I–V) characteristics of the diode is shown in Figure 1. The saturation current has been found to be $\simeq$ 5.1 × 10^{-8} A. The zero-bias barrier height ϕ_{bo} has been calculated to be 0.73 eV [6], using effective Richardson constant of 110 A cm^{-2} K^{-2}. The diode series resistance has been extracted by measuring the constant slope (dV / dI) at the current of the order of 10^{-3} A. The measured (I–V) characteristics of the diode has been corrected for the series resistance. The voltage values V_t and V_s for both forward and reverse biases have been calculated from the corrected (I–V_d) characteristics using eqs. (1) and (2).

From the plots of V_t *vs* V_d, the derivative (dV_t/dV_d) has been found at different values of V_d for both forward and reverse biases. These in turn, give the values of n and s from eqs. (3) and (4), which are bias-dependent as shown in Figure 2. It has been observed that usually s decreases with increasing reverse bias, while n increases usually with increasing forward bias. However, it has also been noticed that sometimes n decreases with increasing forward bias at high biases.

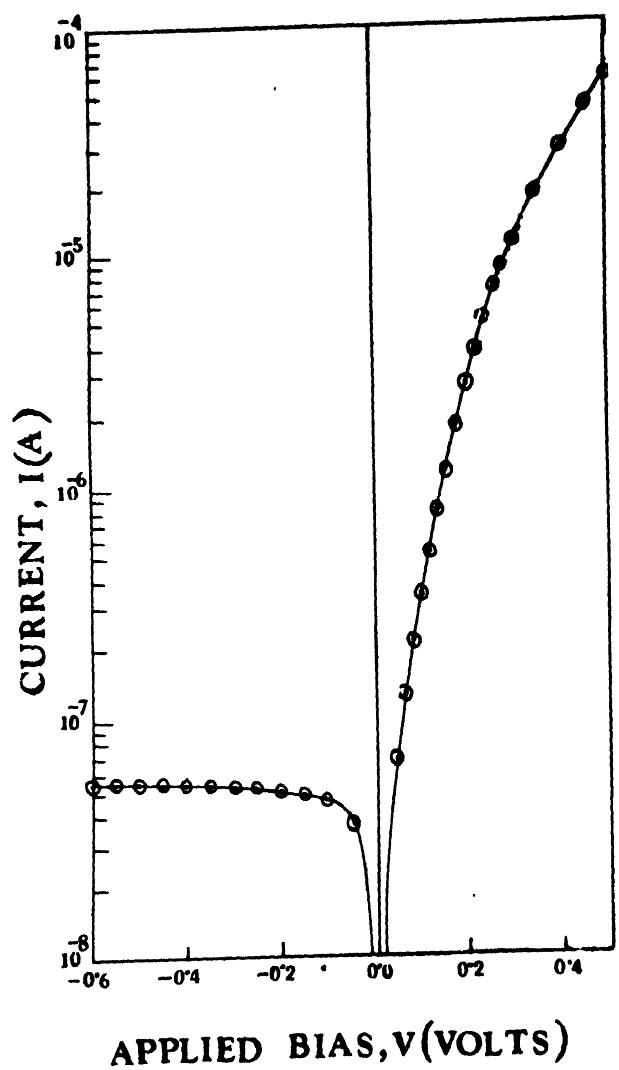

Figure 1. Measured current-voltage (I–V) characteristics of the diode.

The interface state density D_s and the relative interfacial layer thickness δ/ε_i have been determined using eqs. (5) and (6). The interface state density has been found to be of

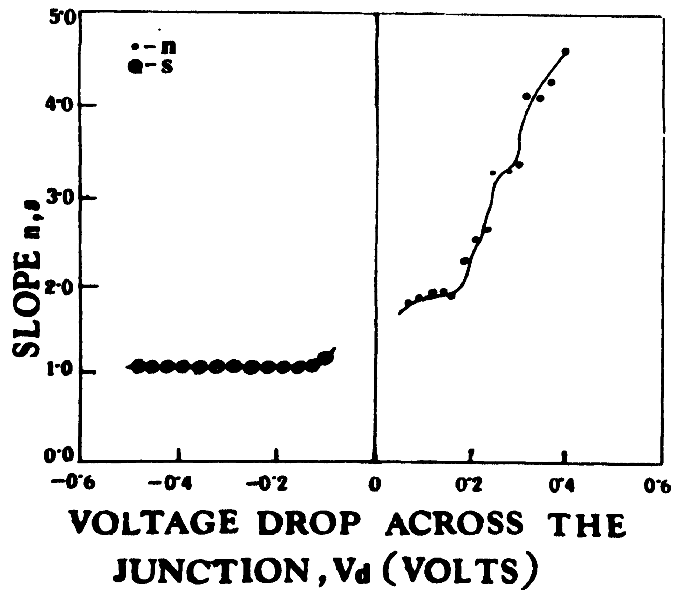

Figure 2. Variation of n and s with V_d under forward and reverse directions

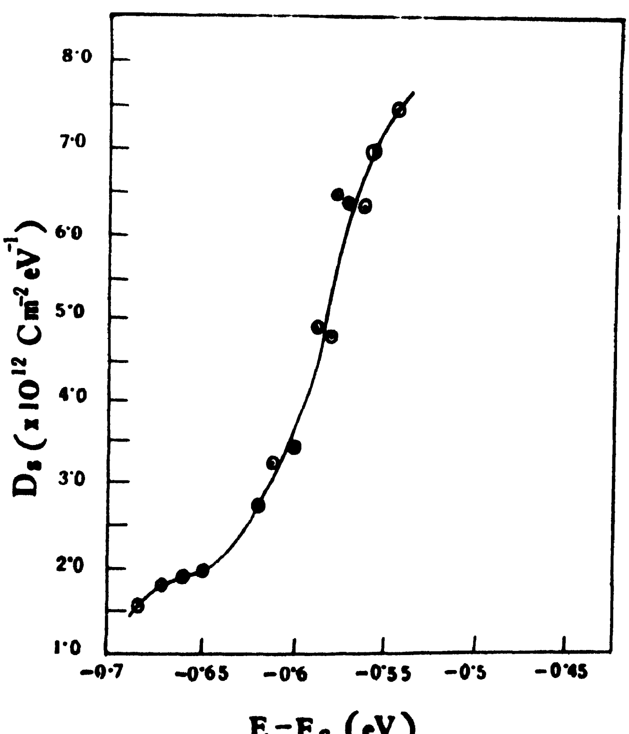

Figure 3. Energy distribution spectra of interface states.

the order of 10^{12} cm^{-2} eV^{-1} while the evaluated relative interfacial layer thickness is (2.5 ± 0.2) nm. The high relative interfacial layer thickness indicates that the interfacial layer is not of SiO_2 only but it is a combination of SiO_2 and some compound having low relative dielectric constant, formed during the fabrication of the diodes. The energy distribution spectra of interface states is shown in Figure 3.

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